Mines and Minerals Division

Ontario Geological Survey
Open File Report 5691

Ontario Geoscience Research Grant Program

Grant No. 267

Platinum - Group Element Abundances in Mafic and Ultramafic Rocks: Preliminary Geochemical Studies at the Lac des Iles Complex, District of Thunder Bay, Ontario

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Ministry of
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by

G.E. Brugmann and A.J. Naldrett

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ONTARIO GEOSCIENCE RESEARCH GRANT FUND

Final Research Report

Foreword

This publication is a final report of a research project that was funded under the Ontario Geoscience Research Grant Program. A requirement of the Program is that recipients are to submit final reports within six months after termination of funding.

A final report is designed as a comprehensive summary stating the findings obtained during the tenure of the grant, together with supporting data. It may consist, in part, of reprints or preprints of publications and copies of addresses given at scientific meetings.

It is not the intent of the Ontario Geological Survey to formally publish the final reports for wide distribution, but rather to encourage the recipients of grants to seek publication in appropriate scientific journals whenever possible. The Survey, however, also has an obligation to ensure that the results of the research are made available to the public at an early date. Although final reports are the property of the applicants and the sponsoring agencies, they may also be placed on open file. This report is intended to meet this obligation.

No attempt has been made to edit the report, the content of which is entirely the responsibility of the author(s).

V.G. Milne
Director
Ontario Geological Survey

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GRANT 276 PLATINUM-GROUP ELEMENT ABUNDANCES IN MAFIC AND ULTRAMAFIC ROCKS: PRELIMINARY GEOCHEMICAL STUDIES AT THE LAC DES ILES COMPLEX, DISTRICT OF THUNDER BAY, ONTARIO

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ABSTRACT

The Lac des Iles Complex consists of several mafic and ultramafic intrusive phases, which contain platinum-group element- (PGE) bearing Ni-Cu sulfide mineralization of economic interest. The different plutonic centers have been studied using geochemical and isotopic methods to constrain their petrogenesis. Platinum-group element abundances are used to investigate the origin of the sulfide mineralization and to develop concepts useful for exploration.

Sm-Nd isotope analysis of whole rock samples and mineral separates from the southern ultramafic centre define a $^{143}Nd/^{144}Nd$ vs. $^{147}Sm/^{144}Nd$ isochron with an age of 2738 $\pm$ 27 Ma and an initial $^{143}Nd/^{144}Nd$ of .509149 $\pm$ 29 (ε_{Nd}= +1.3 at T=2738 Ma). This age is interpreted to be the time of emplacement of the ultramafic complex. The southern ultramafic centre consists of a wehrlite core, which is surrounded by websterite and gabbronorite cumulates. Major and trace element variations reflect the zoning of the complex. The MgO, Cr and Ni contents decrease, whilst Al_2O_3, Na_2O, TiO_2, Zr, Y and rare earth element (REE) contents increase from the core to the margin.

The northern ultramafic centre can be subdivided into at least 3 cyclic units which ideally consist of dunite to wehrlite cumulates at the base, overlayn by clinopyroxenite and websterite, which locally grades into gabbronorite. This indicates similar crystallization sequences in both ultramafic centers: olivine, olivine+clinopyroxene, clinopyroxene, clinopyroxene+orthopyroxene, and clinopyroxene+orthopyroxene+ plagioclase.

The gabbroic complex has been subdivided into eastern and western intrusive phases, which consist mainly of gabbro, and norite to gabbronorite cumulates, respectively. Latter phases host PGE-bearing mineralization and appear to intrude the gabbroic cumulates. Compared to the western gabbro, the eastern

gabbro is depleted in MgO, Cr, and Ni but has similar Al_2O_3, CaO and Na_2O contents. This implies different parental magma compositions. REE and Nd isotope ratios in noritic to gabbronoritic intrusive phases of the western gabbro suggest that they are formed from chemically different parental magmas.

Both ultramafic and gabbroic intrusions of the Lac des Iles Complex contain PGE-bearing Ni-Cu sulfide mineralization. However, differences in chalcophile element patterns suggest different ore formation processes. The mineralization of the gabbroic part is characterized by rather constant and very low Ir, but high and variable Au, Pd, and Pt abundances. Its association with pegmatitic gabbro and the high Pd/Ir ratios of the order of 10,000 imply a late stage magmatic origin. Sulfide saturation was probably caused by mixing of gabbronoritic magma with silica and volatile-rich components, which were provided either by assimilation of older continental crust or by mixing with a volatile-rich eastern gabbro. Sulfides in the ultramafic part are characterized by much lower Pd/Ir ratios (10-30) and are typical for sulfides formed from mafic magmas. Mineralization occurs in cumulates of websteritic to gabbronoritic compositions, at the base of harzburgitic to lherzolitic rocks. This might represent a zone of mixing of fractionated residual liquid with fresh pulses of more primitive magma, which caused sulfide liquation.

PLATINUM-GROUP ELEMENT ABUNDANCES IN MAFIC AND ULTRAMAFIC ROCKS: PRELIMINARY GEOCHEMICAL STUDIES AT THE LAC DES ILES COMPLEX, DISTRICT OF THUNDER BAY, ONTARIO

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INTRODUCTION

This research project is primarily concerned with the problem of understanding the behaviour of platinum-group elements (PGE) during formation and fractional crystallization of mantle-derived magmas and the origin of associated PGE mineralization. The study area is the Lac des Iles Complex, approximately 80 km northwest of Thunder Bay (Fig. 276.1). During the one year project, main emphasis was given to the major and trace element characteristics of the different rock suites and to the noble metal distribution. The investigation will form the basis of future studies on variations of noble metals in whole rocks and mineral separates, in order to understand the processes that lead to their concentration, and to develop criteria useful for exploration.

Geological background

The Lac des Iles area belongs to the Wabigoon Subprovince and has recently been mapped by Sutcliffe (1986). It consists of several mafic intrusive phases, which intrude gneissic tonalite of Archean age. The mafic intrusions are arranged about the perimetre of an approximately 30 km diametre circle, the centre of which is composed of hornblende tonalite and biotite granodiorite/tonalite rocks, which were emplaced contemporaneously to the mafic plutons. The Lac des Iles Complex is the largest of the mafic bodies and has been mapped by Pye (1968) and Sutcliffe and Sweeney (1985, 1986). These authors distinguished an ultramafic part located around Lac des Iles and a gabbroic part to the south of the lake (Figure 276.1). Absolute ages are not published and age relationships between the different intrusive phases are not well understood.

Previous studies of the gabbroic part concentrated on several occurrences of PGE-bearing sulfide mineralization especially the Roby Zone (Dunning, 1979; Watkinson and Dunning, 1979; Talkington and Watkinson, 1984; Macdonald, 1985, 1987; Sweeny and Sutcliffe, 1986). Based on mineralogical and chemical differences, Dunning (1979) distinguished between two intrusive phases, a gabbroic eastern phase (plagiclase-clinopyroxene- cumulates) and a noritic to gabbronoritic western phase (orthopyroxene-clincpyroxene- ±plagioclase cumulates). However, primary mineralogy is rarely preserved, as plagioclase is altered to sericite, epidote and chlorite, and pyroxene is replaced by amphibole. Occasionally, websterite and gabbronorite samples contain fresh

mineral grains. Macdonald (1985, 1987) and Sweeny and Sutcliffe (1986) have mapped part of the gabbroic intrusion in detail and have shown that the interface between eastern and western gabbro is very complex and heterogeneous on a centimetre and metre scale. It consists of melanocratic to leucocratic and coarse-grained to pegmatitic gabbro and gabbro breccia and is intruded by websterite to gabbronorite and tonalite dykes (Macdonald, 1987). Sweeney and Sutcliffe (1986) interpreted this zone, which hosts the major PGE mineralization of the Roby Zone, to be the result of magma mixing between the eastern and western gabbro. Metals of economic significance are Pd, Pt and Au. Based on noble metal abundances and the lithological association Macdonald et al. (1987) distinguished 3 categories of mineralization:

a. low grade mineralization (less than 1000 ppb PGE+Au) occurring in pegmatoidal gabbro, leucocratic gabbro and gabbro breccia;
b. mineralization with up to 15 ppm PGE+Au associated with an intrusive websteritic-gabbronoritic dyke.
c. high grade mineralization (up to 35 ppm PGE+Au) in gabbro pegmatite dikes.

The ultramafic centers at Lac des Iles also contain PGE-bearing sulfide mineralization, but so far they have not been extensively investigated. The southern ultramafic complex consists of a wehrlite core, surrounded by websterite, which grade into gabbronorite (Figure 276.1). The northern ultramafic complex is built up of several cycles of dunite, wehrlite, clinopyroxenite, websterite and gabbronorite. However, due to lack of outcrop single units can often be traced only over tens of metres or even less, and the generally massive structure of the rocks also complicates the interpretation of geometrical relationships between different rock units. These rocks represent meso- to adcumulates and suggest a crystallization sequence of olivine, olivine-clinopyroxene, clinopyroxene, clinopyroxene-orthopyroxene and finally clinopyroxene-orthopyroxene-plagioclase (Sutcliffe and Sweeney, 1985). Olivine is generally completely altered to serpentine and magnetite; occasionally, fresh olivine cores can be observed in thin sections of wehrlites and clinopyroxenites. Pyroxenes and plagioclase are fresh to moderately altered.

Samples and analytical techniques

Samples

Field work in 1986 concentrated on rock sampling and examining detailed geological relationships in the gabbroic and ultramafic complexes. Rock samples were collected along sections, which represent the lithological sequence in the different intrusions. Locations of traverses A, B, and C are indicated in Figure 276.1. Lithological sequences and sample points are shown in the geological profiles of Figures 276.2, 3 and 9.

Analytical methods

Major element chemistry of the rock samples has been determined by conventional X-ray flourescence analysis (XRF) on glass pellets. Trace element determinations, such as Ni, Cr, V, Zr, Y, Rb and Sr, were performed by XRF using powder pellets. REE and Sc have been determined by instrumental neutron activation analysis (INAA). The noble metals Au, Pd, Pt, Ir and Os have been analysed by means of radiochemical neutron activation analysis as described by Brügmann (1985) and Brügmann et al. (1987). Samples have been irradiated at the Slowpoke reactor, University of Toronto, for 16 hours in a thermal neutron flux of $2*10^{11} ns^{-1} cm^{-2}$, or at the reactor of the McMaster University, Hamilton, for 72 hours in a flux of $3*10^{13} ns^{-1} cm^{-2}$. Preliminary Sm-Nd isotope data have been obtained for whole rocks and mineral separates. They have been determined at the Max-Planck-Institut für Chemie, Mainz, F.R.G. The accuracy of the XRF analyses are estimated to be better than 5 %, except for trace elements analyses of Rb, Zr and Y in the concentration range of 2-10 ppm, for which the accuracy is between 10 and 30 %. Due to the very low concentrations REE analyses are sometimes of poor quality, but better than 30%. Sc determinations are better than 5%. Data quality of the noble metal analyses depends on the counting rate for radioactive isotopes. Precision for Au and Ir is generally better than 10%, for Pd, it is better than 20% and for Pt and Os, it is better than 30%. Accuracy of the data has been estimated by comparison with recommanded data for international standards: for sulfide-poor samples (for example Murchinson meteorite) it is similar to previous estimates of Brügmann et al. (1987), within 10% for all elements; however analyses of sulfide-bearing standards (for example SARM-7) show larger variability, but

accuracy is better than 30%. The lower data reproducibility is probably due to the heterogeneous distribution of noble metals and to the small sample size used in our experiments (nugget effect).

RESULTS AND DISCUSSION

The results of major and trace element determinations are summarized in Table 276.1. Major and trace element variations along the sample traverses of the gabbroic and ultramafic intrusions are shown in Figures 276.2, 3 and 9. Rocks are named using the classification of Streckeisen (1979), based on their normative mineralogy.

Geochemistry of the ultramafic intrusions

Figures 276.2 and 276.3 show lithological profiles and major and trace element variations along the sampling sections in the northern and southern ultramafic intrusions. The following description of the lithological sequences is based on observations made from thin sections and calculations of the normative mineralogy.

The southern centre consists of a wehrlite core, which gradually evolves outwards into olivine-clinopyroxenite and clinopyroxenite. This is surrounded by websterite grading into gabbronorite. This implies a crystallization sequence of: olivine- clinopyroxene, clinopyroxene, clinopyroxene-orthopyroxene, clinopyroxene- orthopyroxene-plagioclase. Major and trace element variations reflect this change from ultramafic to mafic compositions (Figure 276.2). Thus, MgO, Ni and Cr contents systematically decrease from the core to the margin of the intrusion, whereas Al and Sr contents increase indicating the presence of plagioclase. At the same time, concentrations of incompatible elements Na, Ti, Y, Zr, and REEs increase, as well as ratios of selected incompatible elements such as Zr/Ti and Zr/Y. This probably reflects the increasing amount of interstitial liquid and the change from adcumulate to mesocumulate/orthocumulate textures.

Based on lithological repetitions and chemical variations, the northern ultramafic centre can be subdivided into at least three cycles, which are interpreted as either individual intrusions or several influxes of new primitive magma batches into the magma chamber (Figure 276.3). Due to lack of outcrop, the relative position of the central part of the profile in Figure

276.3 is not well defined; it may either represent another cycle (or even several cycles) or the extension of cycle 1 to 3, to give the intrusion a circular shape. Ideally, a cycle consists of a dunite base grading into wehrlite and clinopyroxenite. This is overlain by websterite, which locally grades into gabbronorite. This lithological sequence is very similar to that of the southern ultramafic centre indicating a similar crystallization order and similar parental magma compositions.

Cycle 4 of the northern ultramafic complex (Figure 276.3) consists of a websterite core surrounded by clinopyroxenite and olivine clinopyroxenite. Within the olivine clinopyroxenite a thin, less than 1cm thick chromitite seam has been observed (sample LDI-43). Previous field parties also described thin chromitite seams in olivine clinopyroxenites (Sutcliffe and Sweeney, 1986; Linhardt and Sutcliffe, 1986). This part of the ultramafic complex appears to be a separate intrusion as the lithological sequence does not match those of cycles 1 to 3. Furthermore, no chromitite horizons have been discovered in these cycles. The outcrops of the chromitite seams are indicated in Figure 276.1 and they may define the shape of this separate intrusion.

A few samples from the bases of cycle 1 and 2 have harzburgitic to lherzolitic compositions (samples LDI-22, 23, 35). Thin section examinations of samples from the interface of different cycles revealed that olivine grains are often replaced by orthopyroxene. This implies that olivine was not in equilibrium with its host liquid. However, orthopyroxene is probably not an early liquidus phase of the magma forming the main masses of the two cycles, as websterite cumulates appear later in the lithological sequence. Interestingly, lherzolitic and harzburgitic samples overlie gabbronorite, which contain PGE-bearing sulfide mineralisation. An interpretation of these observations is discussed below (see section on noble metal distribution in the ultramafic centres).

REE data are summarized in Table 276.2. Gabbronorite, websterite, wehrlite and clinopyroxenites display convex patterns and intermediate REE form a pronounced maximum (Figure 276.4). In view of the overall adcumulate textures and the low concentrations of incompatible elements, it is likley that in this complex cumulate minerals control the REE patterns. The convex shape is typical for clinopyroxene which suggests that clinopyroxene is the main REE carrier. Peridotites are light REE enriched relative to intermediate and heavy

REE. Olivine may not contain significant REE contents, due to the very low REE partition coefficients between olivine and silicate magma. Therefore, the REE abundances of the peridotites probably reflect the REE pattern of the interstitial liquid, which should be similar to the pattern of the parental magma.

Sm-Nd-isotope systematics of the ultramafic centers.

Results of Sm-Nd-isotope analyses are reported in Table 276.3. The analysed samples include whole rocks from different ultramafic and mafic intrusions and mineral separates of sample LDI-16 from the southern ultramafic centre. Figure 276.5 shows an isochron diagram for the ultramafic centers. Whole rock and plagioclase, orthopyroxene and clinopyroxene mineral separates from the southern ultramafic complex give an age of 2738 $\pm$ 27 Ma. This agrees very well with ages reported from other mafic intrusions of the Wabigoon province (Morrison et al., 1985; Shirey et al., 1986) and is interpreted as the time of the intrusion of the southern ultramafic magma. The sample of cycle 1 of the northern ultramafic centre also plots along this isochron, indicating a similar age. However, sample LDI-45 of cycle 4 plots significantly below the regression line (error bars for the analyses are much smaller than the symbols). Given a similar age for the amfic intrusions, the parental magma forming this part of the northern ultramafic complex must had different Nd isotope characteristics than the southern centre and the base of the northern ultramafic center. This supports the previous suggestion that cycle 4 represents a separate intrusive phase. ε_{Nd}(T=2738 Ma) values for the southern centre and cycle 1 of the northern centre are about 1 to 1.4 and indicate that the source of the parental magmas had a time-averaged depleted light REE profile relative to CHUR (= chondritic uniform reservoir) for the Archean mantle. However, if we look at Nd isotope data of the tonalites, gabbros and ultramafics altogether, ε_{Nd} values vary significantly between 0 and 2. Brügmann et al. (in prep) conclude that these variations are likely due to assimilation of older continental crust. The alternative explanation is that the mantle source of the parental liquids forming the various Lac des Iles intrusions was heterogeneous on a very small scale.

Noble metal distribution in the ultramafic centers

Occurrences of PGE-bearing Ni-Cu sulfides in the ultramafic complex have previously been reported by Sutcliffe (1986) and Linhardt and Sutcliffe (1986). So far, no high grade mineralisation comparable to that found in the Roby Zone of the gabbroic part of the Lac des Iles Complex has been found. Sulfide mineralization mainly occurs in rocks of websteritic to gabbronoritic composition. Samples studied here contain less than 1 % sulfide and the main sulfide minerals are chalcopyrite, pyrrhotite and pentlandite.

Table 276.4 summarizes PGE concentrations determined in this study. In addition to previous studies it also provides data for Ir and Os. PGE contents in samples of the ultramafic centers vary by up to 2 orders of magnitude. Pd/Ir ratios are typical for mafic rocks, ranging from 10 to 30. Figure 276.6 shows chalcophile element patterns of selected samples. Elements are ordered according to increasing incompatibility in silicate liquids and concentrations are normalized to a model primitive mantle composition, represented by spinel lherzolites (Jagoutz et al., 1979; Mitchell and Keayes, 1981; Morgan et al., 1981). Compared to the common practice of chondrite normalization, this method allows direct comparison of highly chalcophile elements (PGE and Au) with less chalcophile elements (Ni, Co, Cu) in mafic and ultramafic rocks (Brügmann et al., 1987). Figure 276.6 shows two different types of PGE patterns. Samples of websterite and gabbronorite composition are similar in that they are enriched in Au, Pd and Pt relative to Co, Ni, Os and Ir. Such patterns are typical for sulfide-poor and sulfide-bearing mafic and ultramafic volcanic rocks and are probably caused by fractionation during fractional crystallization of silicate and oxide minerals and mantle melting. Thus, Co, Ni and probably Ir are compatible to mafic minerals such as olivine, and their concentration in magmas decrease with fractional crystallization of such minerals. On the other hand, Au, Pd, Pt, and Cu generally are incompatible to silicate minerals and therefore become enriched during fractionation of silicate melts (Naldrett and Barnes, 1986; Brügmann et al., 1987). The adcumulate textured websterite and gabbronorite cumulates have insignificant amounts of interstitial liquid. Therfore, the chalcophile element patterns of these samples are probably controlled by the sulfide phase. Dunite and wehrlite samples display a complementary pattern. They are depleted in Au, Pd and Pt relative to Ir, Os, Ni and Co. This is in agreement with the previous hypothesis, as elements such as Ni, Co and Ir partition into olivine, whereas Au, Pd and Pt are

incompatible. The patterns do also indicate that the dunites and wehrlites contain insignificant amounts of sulfide, because magmatic Ni-Cu sulfides are enriched in Au and Pd relative to Ir, Os, Ni and Co. The low abundances of Au and Pd suggest, that there is only a low amount of interstitial liquid left in the cumulates.

In the ultramafic centers PGE-bearing sulfide mineralization occurs mainly in websterite and gabbronorite and is overlain by peridotite. As already pointed out, peridotite and websterite at the interface contain olivine, which is in disequilibrium with its environment, as it is replaced by orthopyroxene. One explanation could be that, after magma was errupted, the chamber has been replenished with fresh magma, which mixed partly with the remaining, more fractionated liquid. Olivine, which crystallized in the rather primitive magma, settled to the bottom of the chamber into a hybrid magma of more evolved composition. There, it reacted with the melt to form orthopyroxene. Mixing of a mafic magma with a fractionated, silica-rich liquid may also cause sulfide liquation. As pointed out by Irvine (1975) and Naldrett and Macdonald (1980), adding silica to a magma can result in a reduction of the solubility of sulfide causing the eventual formation of an immiscible sulfide liquid. Therefore, it is suggested that sulfide mineralization in websteritic to gabbronoritic rocks of the ultramafic complexes was formed by the mixing of a new input of fresh, more primitive magma with residual, fractioned liquid near the bottom of the magma chamber. Cambell and Naldrett (1979) showed that the PGE content of a sulfide liquid depends on the silicate/sulfide liquid mass ratio, the R-factor. The relatively low PGE concentrations in the sulfide mineralization of the ultramafic part of the Lac des Iles Complex suggest a low R-factor, i.e. sulfide liquid equilibrated with a rather small amount of silicate magma. The mixing of magmas near the bottom of the magma chamber might very well be a local phenomena. Thus, the geochemistry of the sulfide mineralization in the ultramafic centers is consistent with the model.

Nickel contents of the rocks from the ultramafic complexes also suggest that sulfide liquation was a rather small-scale phenomenon. Figure 276.7 shows the variation of Ni along the MgO content of whole rock samples and mineral separates. The Ni contents of the clinopyroxenite, and of most of the websterite and gabbronorite cumulates are controlled by the modal abundances of the constituent minerals, because they plot in the triangle built up by orthopyroxene, clinopyroxene and plagioclase. The higher Ni contents of some

Geochemistry of the gabbroic intrusion

Most of the samples of the gabbroic part of the Lac des Iles Complex are pervasively altered and idenfication of the primary mineralogy using thin sections and chemical mineral analysis is often impossible. Similarily, calculation of the normative mineral content heavily depends on the assumption, that this alteration was isochemical and that redistribution of elements was insignificant. Samples of the eastern gabbro display inconsistencies between normative mineralogies and field descriptions, which could indicate that certain major elements were mobile during alteration. Thus, previous workers describe eastern gabbro rocks as plagioclase-clinopyroxene cumulates, whereas normative mineral calculations indicate the presence of significant amounts of orthopyroxene (samples LDI-8, 10, 57). This could imply redistribution of elements like SiO_2 and CaO, which are known to be very susceptible to alteration. However, comparison with immobile elements, such as Al_2O_3 and Sc (calculations of normative orthopyroxene and clinopyroxene are also independent of these elements), indicates that this is probably not the explanation. Thus, in Figure 276.8 samples of the eastern gabbro clearly plot in the ternary space of clinopyroxene, plagioclase and orthopyroxene. The variation of CaO and Al_2O_3 is almost identical (Figure 276.9) as are variations including elements such as MgO, FeO Na_2O and Sr (not shown here). Estimates of the amount of plagioclase, orthopyroxene and clinopyroxene, based on these element variations, are in good agreement with the normative mineralogy calculations. This suggests that during the alteration of the gabbroic complex major elements did not experience extreme redistibution and that eastern gabbro rocks also contain orthopyroxene. An alternative explanation is that magmatic hornblende was an important crystallizing mineral phase. Thus, in the variation diagram of CaO and Al_2O_3 (Figure 276.9) eastern gabbroic rocks plot close to a mixing line between plagioclase and hornblende. To date, however, magmatic hornblende has not been unambiguously identified in the eastern gabbro . It is a common crystallizing phase in most of the mafic intrusions of the Lac des Iles area (Sutcliffe, 1986), and even in gabbronoritic rocks of the western gabbro and the ultramafic complexes primary hornblende has been observed. It is interesting that leucogabbros of the southwestern part of the gabbroic intrusion (samples LDI-60 to 64), which have been described as plagioclase-clinopyroxene cumulates, display similar chemical characteristics

as rocks from the eastern gabbro. Normative mineralogy calculations also indicate the presence of orthopyroxene. Intensive microprobe analysis are required to eluicidate this problem, which is of major importance for the interpretation of the petrogenesis of the gabbroic complex.

Previous workers subdivided the gabbroic intrusion into a eastern and western gabbro (Dunning, 1979; Watkinson and Dunning, 1979; Sweeney and Sutcliffe, 1986) and interpreted them as separate not comagmatic phases. This is based on:

a. mineralogical differences; the eastern gabbro has no orthopyroxene, is oxide-rich (magnetite), and sulfide poor, whilst the western gabbro contains orthopyroxene as a cumulus phase, and is the source of sulfur and the ore metals, which give rise to the mineralization in the Roby Zone.
b. chemical differences; the eastern gabbro is more fractionated having lower Mg-numbers (MgO/MgO+FeO) and higher Al_2O_3 and CaO contents than the western gabbro.

In detail his subdivision is more complex. For example, the southwestern part of the western gabbro also contains leucogabbro, which is very similar to eastern gabbro rocks. It also contains magnetite-rich zones (Macdonald, 1987; pers. communication). On the other hand, the eastern gabbro contains gabbronoritic rocks (samples LDI-6, 7, 9). This zone appears to be intrusive into leucogabbro (Sweeney and Sutcliffe, 1986) and is associated with PGE-bearing sulfide mineralization (B- and H-Zones, after Pye (1968)).

Figure 276.10 shows major and trace element variations along a profile through the gabbroic complex. At the contact of western to eastern gabbro MgO/MgO+FeO (Mg#) clearly decreases from about 0.75 to less than 0.65 confirming observations of previous studies. Similarily, concentrations of Ni and Cr decrease (Figure 276.10). The variations of Al, Ca, Na and Sr do not indicate significant differences between the two gabbroic phases. Incompatible trace elements such as the REE, Rb and Zr also show no systematic trends. Their abundances are probably controlled by the amount of interstitial liquid in the cumulates. Surprisingly, gabbronorites of the B- and H-zone in the eastern gabbro also have lower Mg#, and lower Ni- and Cr-contents than most rocks of the western gabbro. However, the estimated Mg# of these gabbronorites may be too low as they contain cumulus magnetite (1-2 %). This is also indicated by high concentrations of Ti, V, Co and Sc (Figure 276.10, Table 1), elements which strongly partition into magnetite. As the chilled margin sample LDI-9,

which contains no visible magnetite, also has low Mg#, the influence might be insignificant. A gabbronorite dyke in western gabbro (LDI-55) also has a lower Mg#, comparable to those of the eastern gabbro. The different Mg# and Ni and Cr concentrations of western and eastern gabbbro and between gabbronoritic phases suggest that they originated from different parental magma. For example, a Mg# versus Al_2O_3 variation diagram indicates two different, but parallel trends of Al_2O_3 (plagioclase) enrichment (Figure 276.11): at comparable Al_2O_3 contents samples from the eastern gabbro and sample LDI-55 have significantly lower Mg# than websterite and gabbronorite samples from the western gabbro, and the ultramafic complex. The diagram suggests that plagioclase crystallization started at different Mg#. This variation could be the result of the crystallization of two magmas with different compositions.

REE patterns and preliminary Sm-Nd isotope data also indicate differences in the composition of the parental liquids of websteritic to gabbronoritic cumulates. These samples have variable REE patterns, ranging from flat to light REE enriched (Figure 276.12). Some of the differences in the shape of the REE pattern might be caused by fractionation of clinopyroxene or hornblende. However, gabbronorites with light REE enriched and flat REE patterns have similar low ε_{Nd} values of about 0 (samples LDI-6, 55; Table 276.3), whereas one norite with a light REE enriched pattern has a significant higher ε_{Nd} value of about 2 (sample LDI-03; Table 276.3). The variable ε_{Nd} values suggest that, during uprise through older continental crust the parental magma of these gabbronorites has been contaminated with variable amounts of an crustal component. An alternative interpretation is that the parental liquids of the gabbronoritic phases formed in mantle sources with different REE and isotopic composition. Leucogabbros of the eastern gabbro are light REE enriched and show large positive Eu anomalies, as expected in plagioclase cumulates (Figure 276.12). Leucogabbros of the southwestern part of the western gabbro display similar REE patterns (Macdonald, pers. communication) and could suggest a common origin with gabbros of the eastern gabbro. The different Mg# in these gabbros do not necessarily imply a different source magma, because the Mg# of mafic minerals would change concurrently with progressive fractionation of a silicate liquid. Therefore, Mg# of anorthosite cumulates, where Mg# will be controlled by the FeO-MgO bearing mafic minerals, should decrease during evolution of the parental melt.

Constrained by the geological and geochemical evidence summarized above the following tentative model for the genesis of the gabbroic complex is proposed: intrusion of a mafic magma forming the leucogabbro cumulates of the eastern and western gabbro; shortly after, several geochemically distinguished websterite/gabbronorite phases were emplaced. This intrusion sequence appears to be well constrained due to the occurrence of discordant websterite to gabbronorite dykes in leucogabbro. The relatively good preservation of the orthopyroxene bearing rocks compared to the pervasively altered leucogabbros might also indicate that they were emplaced after alteration of the leucogabbros. However, the occurrence of ductile deformation and mixing phenomena implies that leucogabbro cumulates were not completely solidified at the time of websterite-gabbronorite intrusion. To explain the severe alteration of the leucogabbro we suggest a volatile-rich parental magma. If this is the case, hornblende was most probably a liquidus phase of the eastern gabbro magma - together with plagioclase and ±clinopyroxene - , which would explain the major and trace element characteristics of the leucogabbros. This volatile-rich component could also be the highly fractionated interstitial liquid of the leucgabbro cumulates. Alternatively, the volatile-rich phases were introduced by tonalite magmas, which intrude the gabbro.

Noble metal geochemistry of the gabbroic complex

The PGE deposit at the interface of western and eastern gabbro (Roby Zone) has been explored in great detail over the last decade and it is one of the most developed prospects in North America. PGEs occur in sparsely disseminated sulfides (chalcopyrite, pyrrhotite, pentlandite, and pyrite) in pegmatoidal gabbro, pegmatite dykes, anorthositic lenses, websterite-gabbronorite dyke and magmatic breccias (Macdonald et al., 1987). Dunning (1979) and Watkinson and Dunning (1979) describe braggite and vysotskite as the most abundant platinum-group minerals (PGM). The high grade mineralized zones appear to be spatially associated with the websteritic-gabbronoritic intrusions.

Figure 276.10 shows the distribution of the chalcophile elements Au and Ni along the profile through western and eastern gabbro. Compared to the western gabbro, the eastern gabbro has significantly lower Au and Ni contents. With the exception of the magnetite bearing samples, this gabbro has also lower Co contents. One explanation could be that the eastern gabbro is depleted in chalcophile elements due to the segregation of an immiscible sulfide liquid.

However, given a sulfide-silicate partition coefficient in the order of 10^4 to 10^5, the Au contents in the eastern gabbro are far to high to be in equilibrium with a sulfide liquid. Furthermore, beside low Ni and Co contents, the eastern gabbro has also low Cr concentrations. This element usually does not partition into sulfide melts. Therefore, the low abundances of Ni, Co and Cr in eastern gabbro samples are likely to reflect their lower content of mafic minerals, compared to western gabbro rocks. As sulfide minerals have not been observed in thin sections of these samples and sulfur contents of the samples are very low (less than 100 ppm; Table 276.1), Au variation in the eastern gabbro is probably controlled by the amount of interstitial liquid.

If the eastern gabbro is not the source of PGEs this implies that the websterite- gabbronorite suite of the western gabbro may be the source. Indeed, the high PGE grades occur in a discordant, Fe-rich gabbronorite dyke (sample LDI-55; Sweeny and Sutcliffe, 1986; Macdonald, 1987), which contains about 2 % sulfide. Chalcophile element patterns (Figure 276.13) indicate a coherent increase of all chalcophile elements. This probably reflects increasing amounts of sulfide in the samples. Assuming that the sulfide-silicate partition coefficients are similar for all precious metals, we then would expect similar concentration variations and constant Pd/Ir ratios. However, whereas Pd, Pt and Au contents vary by a factor of 50, Ir contents vary only by a factor of 5, which gives rise to variable Pd/Ir ratios. Furthermore, the samples have very high Pd/Ir ratios of more than 1600. Data of Naldrett et al. (1980) even indicate ratios in the order of 10000. These ratios are significantly higher than those observed in magmatic sulfide deposits associated with mafic and ultramafic volcanic rocks (Pd/Ir < 300; Naldrett, 1981). Such high Pd/Ir ratios have only been found in proposed hydrothermal sulfide deposits, like the Rathbun Lake mineralization in northwestern Ontario (Rowell and Edgar, 1986). This implies, that either the Lac des Iles mineralization is of hydrothermal origin or that postmagmatic hydrothermal solutions have changed the primary noble metal distribution. The occurence of pegmatitic phases hosting high grade PGE mineralization clearly indicates the importance of late magmatic processes. However, it appears that these pegmatites formed by crystallization of a mafic intercumulus liquid in the presence of a volatile-rich phase rather than by subsolidus replacement. Field observations show that after the intrusion of the mineralized gabbronoritic dyke, pegmatoidal gabbro released fractionated pegmatitic dykes,

which eventually crystallized as anorthositic, quarz-bearing dykes (Macdonald, 1987). During this fractionation, there appears to be a coherent increase in concentrations of Au, Pd and Pt with REE (Macdonald et al., 1987). This suggests that during crystallization of the late magmatic residual liquid, Au, Pd, and Pt behave as incompatible elements and eventually formed higher grade mineralization in pegmatitic dykes. The coherent increase of incompatible elements such as REE in mineralization associated with pegmatite phases, suggests that during extensive fractional crystallization of a late stage, volatile-rich liquid Au, Pd and Pt become enriched in the liquid phase, whereas compatible elements, such as Ir, Ni and Co partitioned into residual minerals. The extreme fractionation eventually caused sulfide saturation and gives rise to the formation of Au, Pd and Pt-rich, but Ir-, and probably also Os- and Ru-poor, mineralization.

There still remains the problem of the cause of sulfide liquation in the gabbronoritic dyke of the Roby Zone. The close association of mineralization with pegmatitic gabbro could imply that mixing of a more primitive mafic-ultramafic melts with patches of fractionated, volatile-rich liquids/fluids caused sulfide saturation. The volatile-rich component could be either residual, interstitial liquid of the early leucogabbro cumulates, or could be introduced with tonalite intrusions. The mineralized gabbronorite dyke contains interstitial magmatic hornblende and has an exeptionelly low ε_{Nd} value (sample LDI-55, Table 276.2). This favours the idea that mixing of mafic-ultramafic magma with crustal components triggered sulfide liquation.

CONCLUSIONS

The Lac des Iles Complex, District of Thunder Bay, consists of several mafic and ultramafic intrusive phases, which contain economically interesting PGE-bearing Ni-Cu sulfide mineralization. The different plutonic centers have been studied using geochemical and isotopic methods to constrain their petrogenesis. Platinum-group element abundances are used to develop concepts explaining the origin of the sulfide mineralizations.

Previous workers distinguished between a gabbroic complex and an ultramafic complex, the latter can be further subdivided into northern and southern intrusive bodies. Sm-Nd isotope analysis of whole rock samples and mineral separates from the southern ultramafic centre define a $^{143}Nd/^{144}Nd$ vs. $^{147}Sm/^{144}Nd$ isochron with an age of 2738 $\pm$ 27 Ma and an initial $^{143}Nd/^{144}Nd$ of .509149 $\pm$ 29 (ε_{Nd}=+1.3). This age is interpreted to be the time of intrusion of the ultramafic complex. The positive ε_{Nd} value indicates an time-integrated depletion in Sm/Nd relative to CHUR for the Archean mantle beneath this area. REE characteristics show that the mafic to ultramafic parental liquids are light REE enriched relative to intermediate and heavy REEs. This implies that either the magmas assimilated incompatible element-rich continental crust during its uprise, or a "metasomatic" enrichment of the mantle source occurred shortly before magma eruption.

The southern ultramafic centre consists of a wehrlite core, which is surrounded by websterite and gabbronorite. All samples represent cumulates with adcumulate to orthocumulate textures. Major and trace element variations reflect the zoning of the complex, in that MgO, Cr and Ni contents decrease, and Al_2O_3, Na_2O, TiO_2, Zr, Y and REE contents increase from the core to the margin. Based on petrographic and geochemical studies the northern ultramafic centre can be subdivided into at least three cyclic units which ideally consist of dunite to wehrlite cumulate at the base, followed by clinopyroxenite and websterite, which locally grades into gabbronorite. These cyclic units are interpreted to represent new inputs of fresh, primitive magma into the magma chamber. Cycle 4 in the northern part of the ultramafic complex might be a separate intrusive body. The magmatic stratigraphy in both ultramafic centers suggests the crystallization sequences : olivine, olivine+clinopyroxene, clinopyroxene, clinopyroxene+orthopyroxene, clinopyroxene+orthopyroxene+plagioclase.

The gabbroic complex has been subdivided into eastern and western intrusive phases, which consist of cumulates mainly of gabbroic and noritic to gabbronoritic composition, respectivily. Latter phases host PGE-bearing mineralization and appear to intrude the gabbroic cumulates. Compared to the western gabbro, the eastern gabbro appears to be MgO-, Cr-, Ni- and Co-depleted at comparable Al_2O_3 contents, implying different parental magma compositions. REE and Nd isotope ratios in noritic to gabbronoritic intrusions of the western gabbro also suggest that they formed from chemically distinguished parental magmas.

Both ultramafic and gabbroic intrusions of the Lac des Iles Complex contain PGE-bearing Ni-Cu sulfide mineralization. However, differences in chalcophile element patterns suggest different ore formation processes. Mineralization in the gabbroic complex is characterized by rather low Ir, but high and variable Au, Pd and Pt abundances. The association with pegmatitic gabbro and the high Pd/Ir ratios in the order of 10000 imply a late stage magmatic origin. A coherent increase of Au, Pd and Pt concentrations with REE contents suggests that high Au, Pd and Pt, but low Ir, Ni and Co contents of mineralizations in pegmatite gabbro are caused by extensive fractional crystallization, which eventually led to sulfide saturation. In the Roby Zone a sulfide saturated, Fe-rich gabbronorite dyke hosts the main PGE mineralization. Here sulfide liquation might be caused by mixing of gabbronorite with a volatile-rich component, which propably originated from crustal components or from deuteric phases of a volatile-rich eastern gabbro. Sulfides in the ultramafic part display chalcophile element patterns typical for deposits associated with mafic and ultramafic volcanic rocks. They are depleted in Ir, Os, Ni and Co relative to Au, Pd and Pt, however, Pd/Ir ratios vary between 10 and 30. Mineralization occurs in cumulates of websteritic to gabbronoritic compositions, at the base of harzburgitic to lherzolitic rocks. This might represent a zone of mixing of fractionated residual liquid with fresh pulses of more primitive magma, which caused sulfide liquation.

Lithological units and geochemical features observed in the Archean Lac des Iles area are very similar to those found in phanerozoic complexes in the North American Cordillera. These complexes also show compositionally zonation, where intrusions of ultramafic to mafic composition are separated by tonalite and granodiorite plutons (Kelemen and Ghiorso, 1986). These complexes also contain abundant hornblende phases, similar to the Lac des Iles area

(Sutcliffe, 1986). Furthermore, gabbro pegmatites are common constituents of mafic intrusive rocks in such complexes (Beard and Day, 1986). Chemical variations are also very similar. For example, trends in AFM diagrams are indistinguishable, following a calc-alkalic fractionation curve. Finally, the western Cordillera also hosts important precious metal mineralization (Levinson, 1981). These observations suggest, that the Lac des Iles Complex may have been formed in a similar tectonic environment - a subject of further research.

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Table 276.1 Major and trace element data for samples from the Lac des Iles Complex
Major elements are recalculated to 100% anhydrous; FeO*=total FeO.

	GABBROIC COMPLEX									
	LDI-01	LDI-02	LDI-03	LDI-04	LDI-05	LDI-06	LDI-07	LDI-08	LDI-09	LDI-10
	NO	GA-NO	NO	GA-NO	L-GA	GA-NO	GA-NO	L-GA	GA-NO	L-GA
SiO_2	51.98	52.29	51.07	50.96	51.32	51.03	50.91	50.53	52.24	50.54
TiO_2	.20	.14	.09	.18	.13	.27	.30	.19	.14	.19
Al_2O_3	14.33	8.47	18.62	17.33	21.10	14.46	13.40	25.08	17.14	24.6
FeO*	10.92	10.72	6.73	6.40	6.47	9.17	9.74	4.94	8.54	5.18
MnO	.21	.22	.12	.13	.11	.16	.19	.07	.16	.08
MgO	12.34	20.66	10.82	10.06	6.12	9.37	10.11	4.37	8.45	4.54
CaO	8.09	6.66	10.50	12.89	11.58	13.65	13.50	11.56	10.67	2.75
Na_2O	1.46	.64	1.63	1.66	2.84	1.76	1.61	2.93	2.43	.26
K_2O	.45	.19	.41	.37	.31	.11	.23	.32	.22	.26
P_2O_5	.02	.01	.01	.02	.02	.02	.01	.03	.01	.02
S wt.%	<.01	.16	.02	.01	<.01	.01	.05	<.01	<.01	<.01
Cr ppm	425	627	205	137	64	38	40	121	100	97
Ni	339	1049	499	321	123	81	89	131	68	117
Co	67	86	46	45	48	67	65	33	37	28
V	163	147	89	170	120	305	331	106	125	113
Rb	17	4	13	11	7		3	8	4	5
Sr	182	43	192	185	293	170	172	357	138	309
Zr	9	4	5	11	6	9	9	14	3	10
Y	3		2	5	2	4	5	2	5	3
Sc	34	41	24	44	35	74	68	16	31	16
Au ppb	13	168	12	12	3	2	4	2	5	2

Table 276.1 continue

	SOUTHERN ULTRAMAFIC COMPLEX									
	LDI-11	LDI-12	LDI-13	LDI-14	LDI-15	LDI-16	LDI-17	LDI-18	LDI-19	LDI-20
	OL-CPX	WHRL	OL-WEB	OL-WEB	OL-WEB	GA-NO	WHRL	GA-NO	GA-NO	GA-NO
SiO_2	51.98	49.00	48.37	49.16	50.88	50.65	45.71	49.22	50.95	50.55
TiO_2	.15	.16	.18	.21	.26	.34	.13	.31	.22	.25
Al_2O_3	1.72	1.69	2.26	6.09	2.78	13.65	1.73	5.26	15.64	11.74
FeO*	6.56	9.60	12.04	11.30	13.59	6.70	13.10	11.10	6.76	9.17
MnO	.18	.18	.22	.21	.27	.14	.24	.22	.15	.2
MgO	20.92	26.41	28.08	21.86	25.23	12.54	30.92	19.58	10.39	14.93
CaO	18.17	12.66	8.57	10.56	6.70	14.66	8.02	13.68	13.69	11.94
Na_2O	.29	.25	.22	.51	.24	1.12	.19	.51	1.61	1
K_2O	.02	.03	.04	.08	.03	.18	.02	.10	.57	.2
P_2O_5	.01	.01	.02	.02	.02	.02	.02	.02	.02	.02
S wt.%	<.01	<.01	<.01	<.01	<.01	.04	.05	.03	.25	<.01
Cr ppm	3783	3564	4415	2660	3644	375	4032	1907	987	1068
Ni	454	803	986	763	784	262	1001	566	314	258
Co	60			77					51	62
V	136	136	154	177	188	188	128	206	170	170
Rb									8	2
Sr	32	20	20	116	22	390	17	96	319	292
Zr	3	5	6	8	9	16	5	15	10	11
Y	4	5	6	6	6	9	4	8	5	6
Sc	69			43					45	55

Table 276.1 continue

	NORTHERN ULTRAMAFIC COMPLEX									
	LDI-21	LDI-22	LDI-23	LDI-24	LDI-25	LDI-26	LDI-27	LDI-28	LDI-29	LDI-30
	GA-NO	HARZ	LHERZ	WEB	OL-WEB	OL-WEB	OL-WEB	GA-NO	WEB	OL-CPX
SiO_2	49.68	42.73	46.81	53.46	51.23	53.08	52.74	51.59	53.62	51.85
TiO_2	.21	.08	.17	.25	.22	.27	.27	.16	.14	.1
Al_2O_3	8.71	1.09	1.79	2.99	2.33	3.17	2.63	11.60	1.64	1.2
FeO*	9.17	12.29	11.97	6.09	9.24	5.95	6.38	7.71	5.36	5.68
MnO	.19	.19	.16	.14	.20	.16	.16	.20	.17	.17
MgO	18.66	43.32	33.07	20.71	25.67	20.30	19.75	16.09	20.31	23.36
CaO	12.47	.20	5.85	16.01	10.88	16.76	17.68	10.65	18.46	17.39
Na_2O	.65	.06	.15	.31	.20	.28	.35	.63	.27	.23
K_2O	.24	.01	.02	.03	.02	.02	.03	1.36	.02	.01
P_2O_5	.02	.02	.01	.01	.01	.01	.01	.01	.01	.01
S wt.%	.36	.02	<.01	<.01	<.01	<.01	<.01	<.01	<.01	<.01
Cr ppm	1562	8662	5387	3393	3968	3285	2820	771	3409	2608
Ni	801	1403	1219	439	621	445	394	251	337	302
Co		109	83		66		50	52	46	0
V	158	76	131	226	175	221	214	151	129	113
Rb	3							24		0
Sr	172	2	16	26	18	24	28	179	29	25
Zr	10	2	6	10	6	8	10	6	4	4
Y	6		5	9	6	9	9	3	4	4
Sc		11	31		54		80	47	55	0

Table 276.1 continue

	LDI-31	LDI-32	LDI-33	LDI-34	LDI-35	LDI-36	LDI-37	LDI-38	LDI-39	LDI-40
	OL-CPX	WEB	WEB	GA-NO	HARZ	DUN	OL-CPX	WEB	OL-CPX	OL-CPX
SiO_2	52.51	52.02	52.34	51.53	45.86	40.63	52.81	53.91	52.78	52.38
TiO_2	.17	.23	.24	.19	.07	.15	.16	.15	.19	.17
Al_2O_3	1.92	2.53	2.86	9.52	.53	2.06	2.00	1.64	2.05	1.64
FeO*	5.56	9.27	9.67	8.09	7.95	14.52	5.63	10.05	4.15	5.64
MnO	.15	.21	.23	.19	.19	.27	.15	.27	.13	.16
MgO	19.31	19.99	20.38	16.09	45.15	40.88	18.83	25.73	20.17	19.85
CaO	20.03	15.50	13.99	13.46	.11	1.35	19.96	8.04	20.17	19.85
Na_2O	.32	.22	.25	.72	.09	.11	.39	.19	.34	.28
K_2O	.02	.01	.02	.20	.02	.01	.06	.01	.01	.01
P_2O_5	.01	.01	.01	.01	.02	.02	.01	.01	.01	.01
S wt.%	.08	.19	<.01	<.01	<.01	.04	.01	<.01	<.01	<.01
Cr ppm	3170	1631	1270	909	3540	22834	2854	3124	4680	2230
Ni	474	461	326	259	1803	2004	323	418	391	334
Co		68		58						0
V	93	239	241	190	43	106	122	131	130	133
Rb				2						0
Sr	40	16	22	227	3	4	39	13	36	31
Zr	8	6	7	7		2	8	3	7	7
Y	5	7	7	6	2		6	3	7	5
Sc		81		60						0

	LDI-41	LDI-42	LDI-43	LDI-44	LDI-45	LDI-46	LDI-47	LDI-49	LDI-54	LDI-55
	WEB	CPX	OL-WEB	WEB	WEB	WEB	WEB	HARZ	GA-NO	GA-NO
SiO_2	52.64	53.52	52.68	53.03	53.89	53.76	53.32	43.75	51.16	52.01
TiO_2	.22	.11	.16	.17	.13	.16	.17	.07	.11	.29
Al_2O_3	2.35	1.28	2.05	1.69	1.54	2.08	2.45	.59	19.19	8.5
FeO*	9.20	4.99	6.43	6.79	9.70	10.52	6.29	12.17	5.39	16.37
MnO	.23	.16	.17	.19	.26	.25	.15	.19	.12	.29
MgO	21.76	20.13	21.86	19.37	25.08	28.09	20.28	42.57	10.52	15.16
CaO	13.34	19.52	16.35	18.45	9.20	4.98	16.88	.46	11.14	6.67
Na_2O	.24	.26	.27	.27	.18	.14	.37	.15	2.04	.52
K_2O	.01	.02	.02	.03	.01	.01	.07	.02	.31	.17
P_2O_5	.01	.01	.01	.01	.01	.01	.02	.02	.01	.02
S wt.%	<.01	<.01	<.01	.05	.26	<.01	<.01	<.01	.01	.45
Cr ppm	3010	2590	11070	1820	1350	10860	3120			292
Ni	415	330	546	320	592	692	369			2082
Co										112
V	201	127	149	187	144	143	146			0
Rb						9			10	4
Sr	19	23	25	27	12	8	35	3	205	42
Zr	6	3	5	6	3		13		10	14
Y	6	4	5	6	3	2	6		4	5
Sc										48

Table 276.1 continue

	GABBROIC COMPLEX								
	LDI-57	LDI-58	LDI-59	LDI-60	LDI-61	LDI-62	LDI-63	LDI-64	LDI-65
	NO	L-GA	GA-NO	L-GA	L-GA	L-GA	L-GA	L-GA	L-GA
SiO_2	51.58	57.01	52.38	52.03	50.96	52.48	53.65	53.35	52.11
TiO_2	.16	.11	.12	.08	.10	.12	.15	.12	.16
Al_2O_3	17.13	18.55	18.49	20.48	24.65	16.73	17.31	23.22	17.06
FeO*	9.35	7.34	6.42	6.02	3.84	7.09	7.3	4.42	7.59
MnO	.14	.13	.13	.12	.07	.15	.15	.08	.14
MgO	11.42	6.05	8.77	9.04	5.88	10.60	8.39	4.95	8.82
CaO	8.57	6.07	11.09	9.79	11.44	9.33	10.38	8.15	11.72
Na_2O	1.47	4.35	2.35	2.15	2.39	2.31	2.45	4.20	2.12
K_2O	.16	.34	.23	.27	.64	1.17	.19	1.48	.26
P_2O_5	.02	.02	.02	.01	.02	.02	.02	.02	.02
S wt.%	<.01	.03	.03	.01	<.01	<.01	<.01	<.01	.10
Rb ppm	4	7	4	6	18	32	3	38	6
Sr	207	480	243	265	306	209	294	414	239
Zr	6	11	10	6	10	9	11	8	10
Y	3	2	3	2	3	4	4	3	4
Sc									48

Abbreviations: NO: Norite; GA-NO: gabbronorite; OL: Olivine; WEB: Websterite; CPX: Clinopyroxenite; LHERZ: Lherzolite; HARZ: Harzburgite; L-GA: Leuco-Gabbro (norite).

Table 276.2 REE contents of mafic and ultramafic rocks from the Lac des Iles Complex

	La	Ce	Nd	Sm	Eu	Yb	Lu
GABBROIC COMPLEX							
LDI-01	1.05	1.9	1.2	.28	.19	.32	.04
LDI-02	.36			.18	.05	.41	.06
LDI-03	.74		.89	.2	.11	.24	.05
LDI-04	.8	2.2		.32	.12	.34	.06
LDI-05	.9	2.1		.27	.14	.28	.03
LDI-06	.75	1.9	1.5	.47	.16	.59	.07
LDI-07	.6			.47	.16	.55	.09
LDI-08	2	4.2	1.9	.31	.34	.18	.02
LDI-09	.21			.16	.11	.38	.05
LDI-10	1.27			.3	.25	.17	.04
SOUTHERN ULTRAMAFIC COMPLEX							
LDI-11	1			.7	.16	.4	.07
LDI-14	.5	2.7		.7	.19	.5	.07
LDI-19	.7	2.9		.74	.2	.62	.1
LDI-20	1.1	3		1.02	.23	.55	.11
NORTHERN ULTRAMAFIC COMPLEX							
LDI-22	.59	1.1		.15	.04	.07	
LDI-23	.44			.64	.11	.41	.07
LDI-25	.3	1.9		.76	.17	.5	.06
LDI-27	.57	3.1		1.48	.39	.85	.12
LDI-28	.62			.46	.14	.3	.06
LDI-29	.66	2.6	2	.75	.17	.32	.05
LDI-32	.4	1.54	2.8	1.05	.22	.6	.1
LDI-34	.53	2.1	2.2	.77	.3	.49	.08
LDI-55	1.19		1.89	.52	.19	.63	.11
LDI-65	.98			.38	.19	.48	.07
Prim.Mantle	.64	1.66	1.23	.4	.15	.42	.07

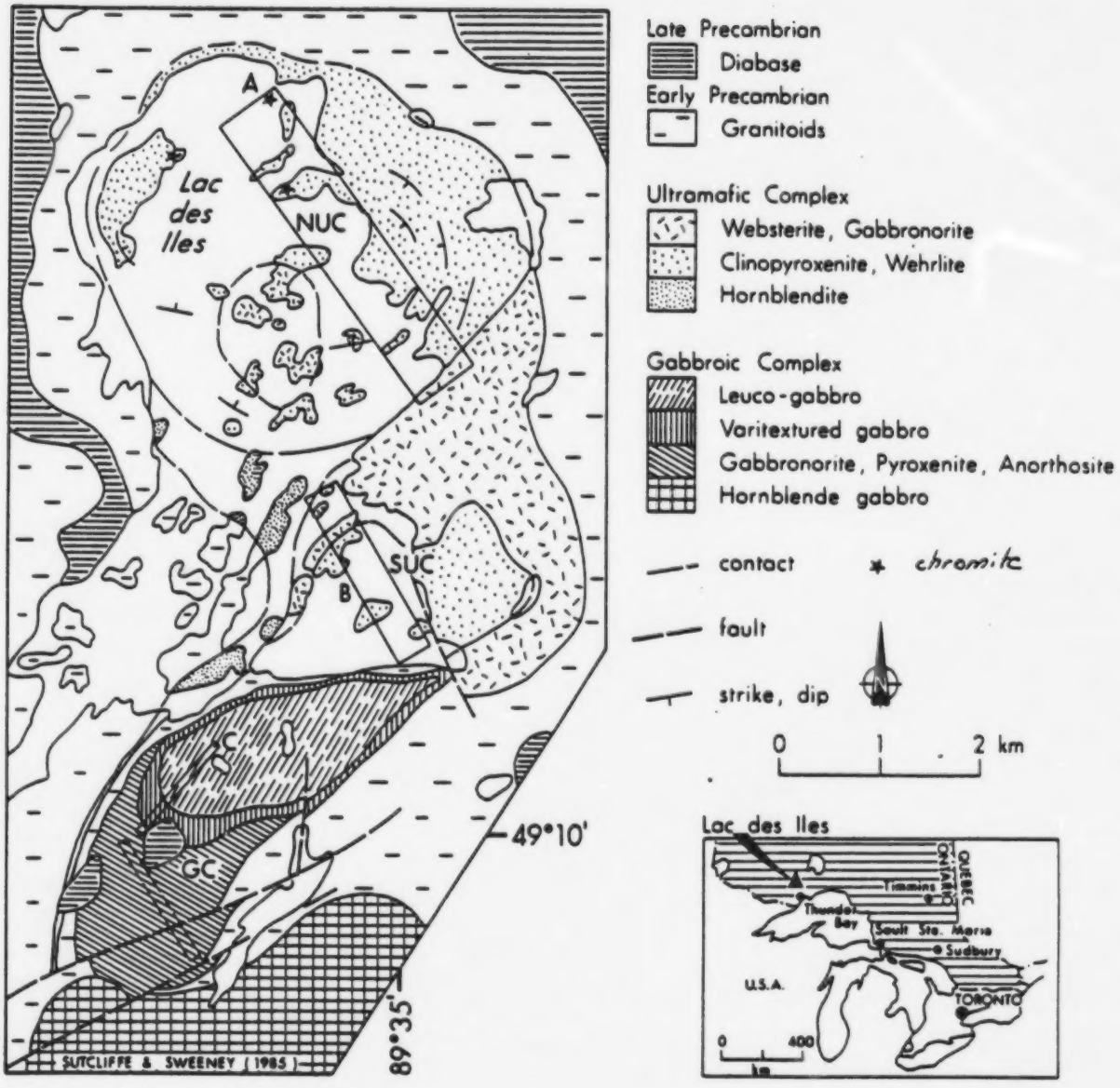
Table 276.3 Nd isotopic data for samples from the Lac des Iles complex.

Sample		Sm ppm	Nd ppm	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	2-sigma Error	ε_{Nd} (T) 2738 Ma
LDI-06	GA.NO	.472	1.51	.189649	.512509	± 16	-.03
LDI-03	GA.NO	.197	.892	.133566	.511595	± 12	1.90
LDI-55	GA.NO	.516	1.89	.164619	.512073	± 10	.28
LDI-17	WEHRL	.565	1.82	.188160	.512553	± 16	1.36
LDI-16	GA.NO	1.37	4.62	.179624	.512400	± 15	1.38
OPX-16	OPX-MI	.402	1.25	.194892	.512676	± 16	1.39
CPX-16	CPX-MI	3.32	10.4	.193920	.512633	+ 18	.89
PLAG-16	PLAG-M	.287	2.41	.071816	.510446	± 17	1.23
LDI-34	GA.NO	.77	2.20	.211213	.512955	± 30	1.08
LDI-45	CPX	.31	1.3	.143865	.511705	± 18	.41

Abbreviations: GA.NO: Gabbronorite; WEHRL: Wehrlite;
OPX-MI: orthopyroxene mineral separate
CPX-MI: clinopyroxene mineral separate
PLAG-Mi: plagioclase mineral separate
CPX: Clinopyroxenite

Table 276.4 Noble metal contents (ppb) in mafic and ultramafic rocks of the Lac des Iles complex

	Au	Pd	Pt	Ir	Os
GABBROIC COMPLEX					
LDI- 2	168	2090	620	.2	
LDI- 4	12.1	110	<50	.1	
SOUTHERN ULTRAMAFIC COMPLEX					
LDI-19	8.7	44	<50	1.9	
LDI-21	16.2	102	40	3.0	
NORTHERN ULTRAMAFIC COMPLEX					
LDI-22	.1	<3	<30	4.5	
LDI-26	1.0	3	<30	1.0	
LDI-27	8.0	35	40	4.0	
LDI-30	3.0	6	<30	.8	
LDI-32	13.7	25	45	5.2	
LDI-34	24	80	109	7.0	
LDI-35	.15		6	3.8	4.1
LDI-36	.13		4	3.7	3.2
LDI-37	5.4		30	2.5	2.3
LDI-38	6.9		42	1.5	.9
LDI-39	.8		4	.4	.7
LDI-41	2.6		26	2.0	2.5
LDI-45	13.9	40	64	3.0	
Prim.Mantle	1.0	4	8	3.6	3.3


A
Lac des Iles
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SUC
B
C
GC
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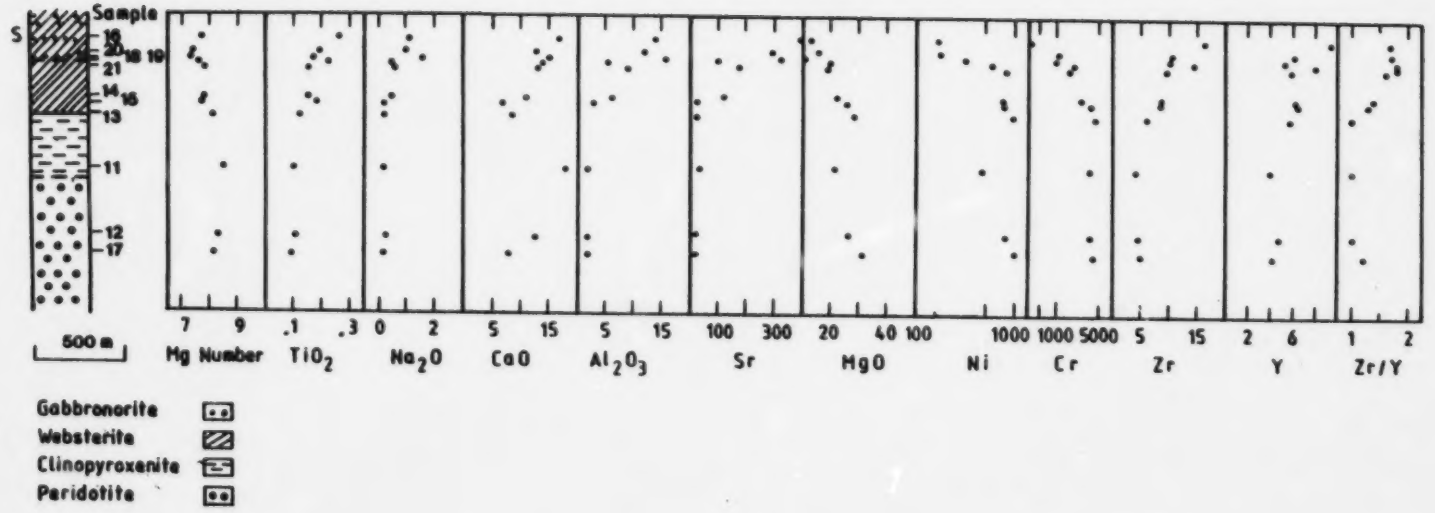
89°35'
SUTCLIFFE & SWEENEY (1985)
Late Precambrian
Diabase
Early Precambrian
Granitoids
Ultramafic Complex
Websterite, Gabbronorite
Clinopyroxenite, Wehrlite
Hornblendite
Gabbroic Complex
Leuco-gabbro
Varitextured gabbro
Gabbronorite, Pyroxenite, Anorthosite
Hornblende gabbro
contact
chromite
fault
strike, dip
N
0 1 2 km
Lac des Iles
ONTARIO
QUEBEC
Timmins
Thunder Bay
Sault Ste. Marie
Sudbury
U.S.A.
TORONTO
0 400
km

Fig 276.1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19
21
14
15
13
11
12
17
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7
9
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Na2O
5
15
CaO
5
15
Al2O3
100
300
Sr
20
40
MgO
100
1000
Ni
1000
5000
Cr
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Zr
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Y
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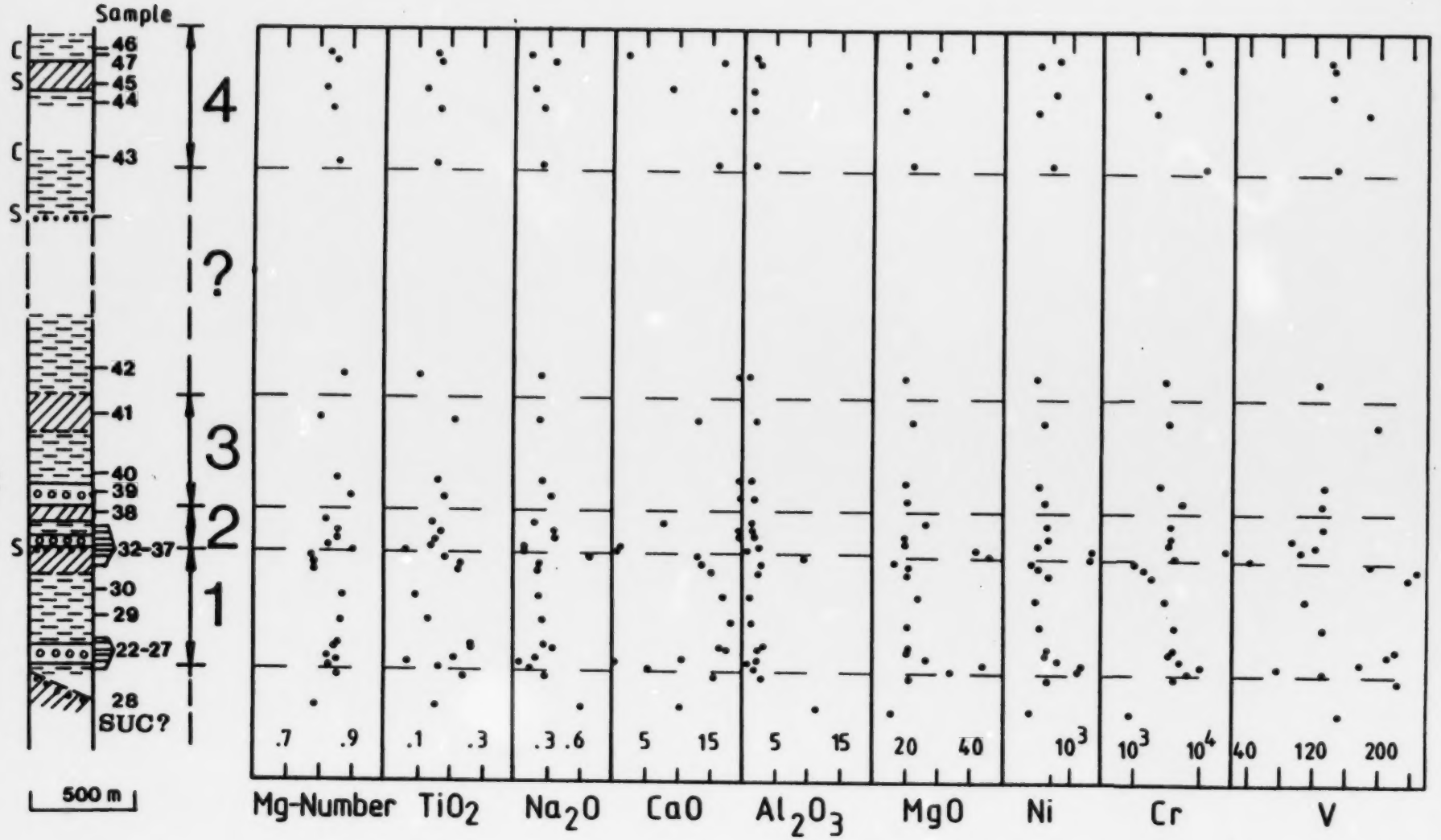
2
Zr/Y
Gabbronorite
Websterite
Clinopyroxenite
Peridotite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S
C
S
S
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47
45
44
43
42
41
40
39
38
32-37
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29
22-27
28
SUC?
4
?
3
2
1
500 m
.7
.9
.1
.3
.3
.6
5
15
5
15
20
40
10³
10³
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MgO
Ni
Cr
V

276.3

276.4

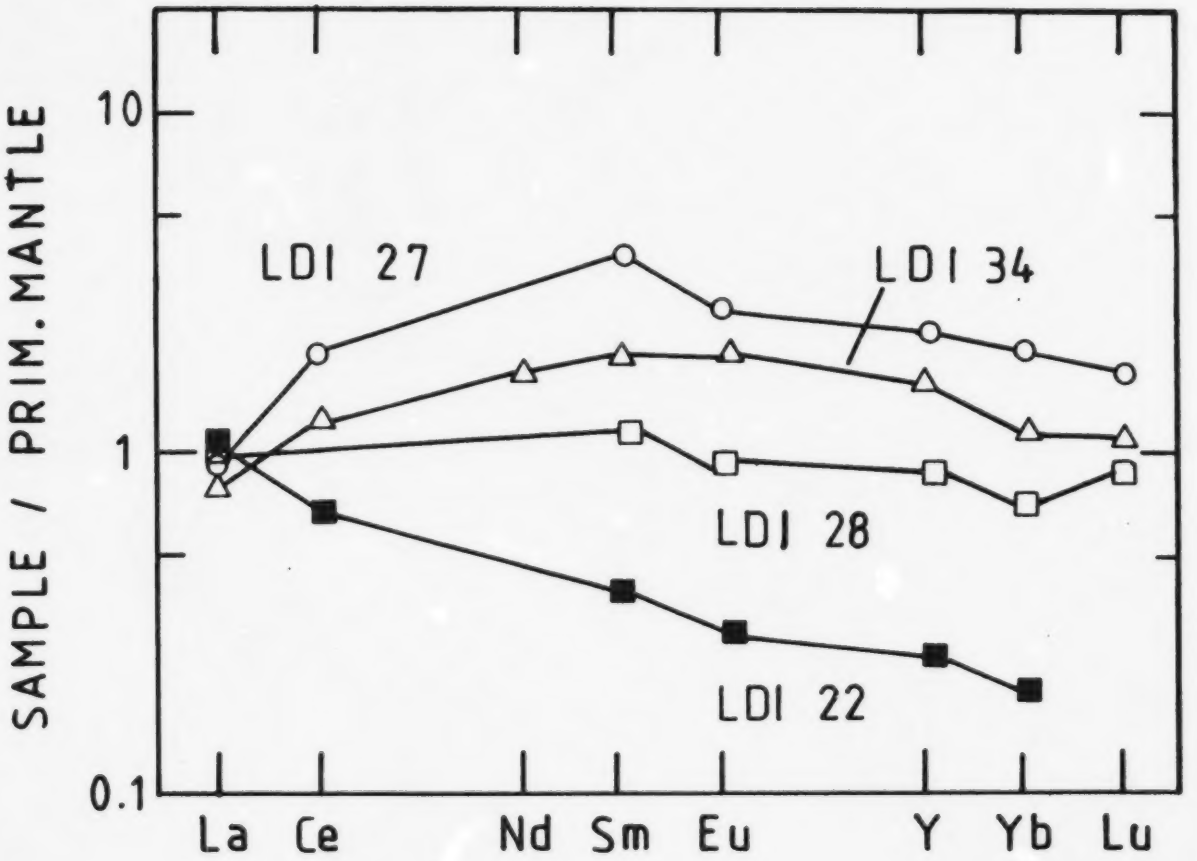


Figure 276.4

276.5

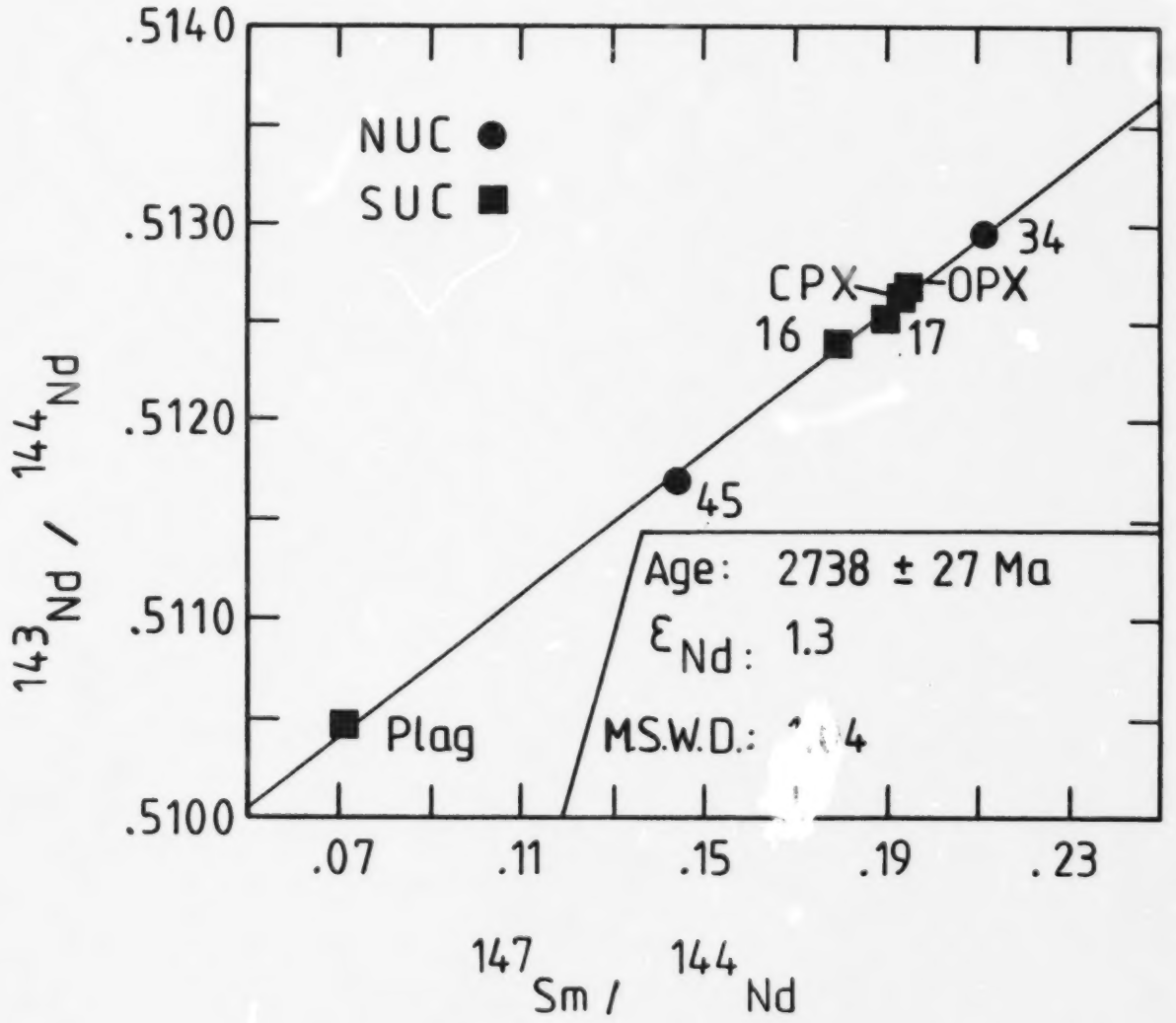
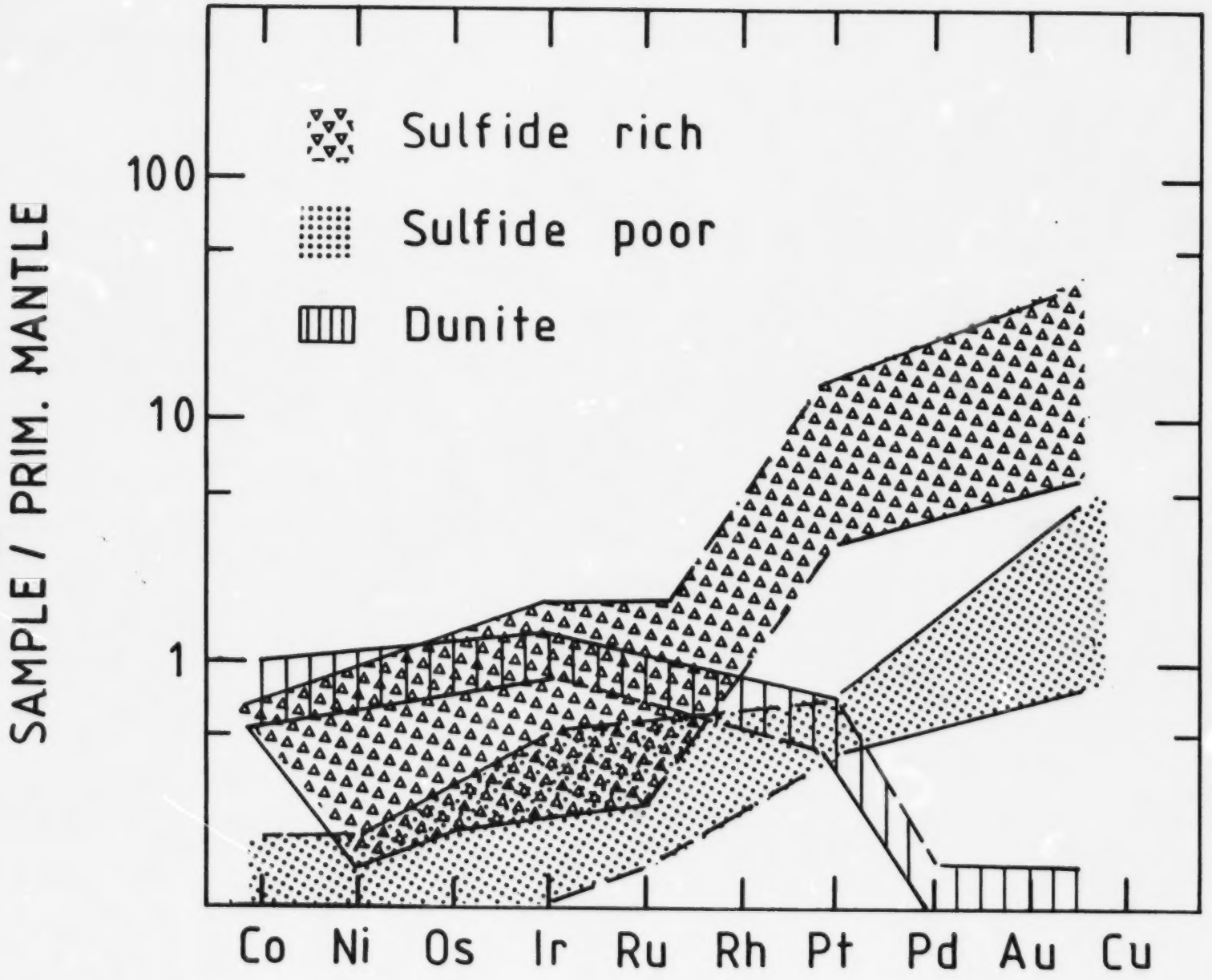


Figure 276.5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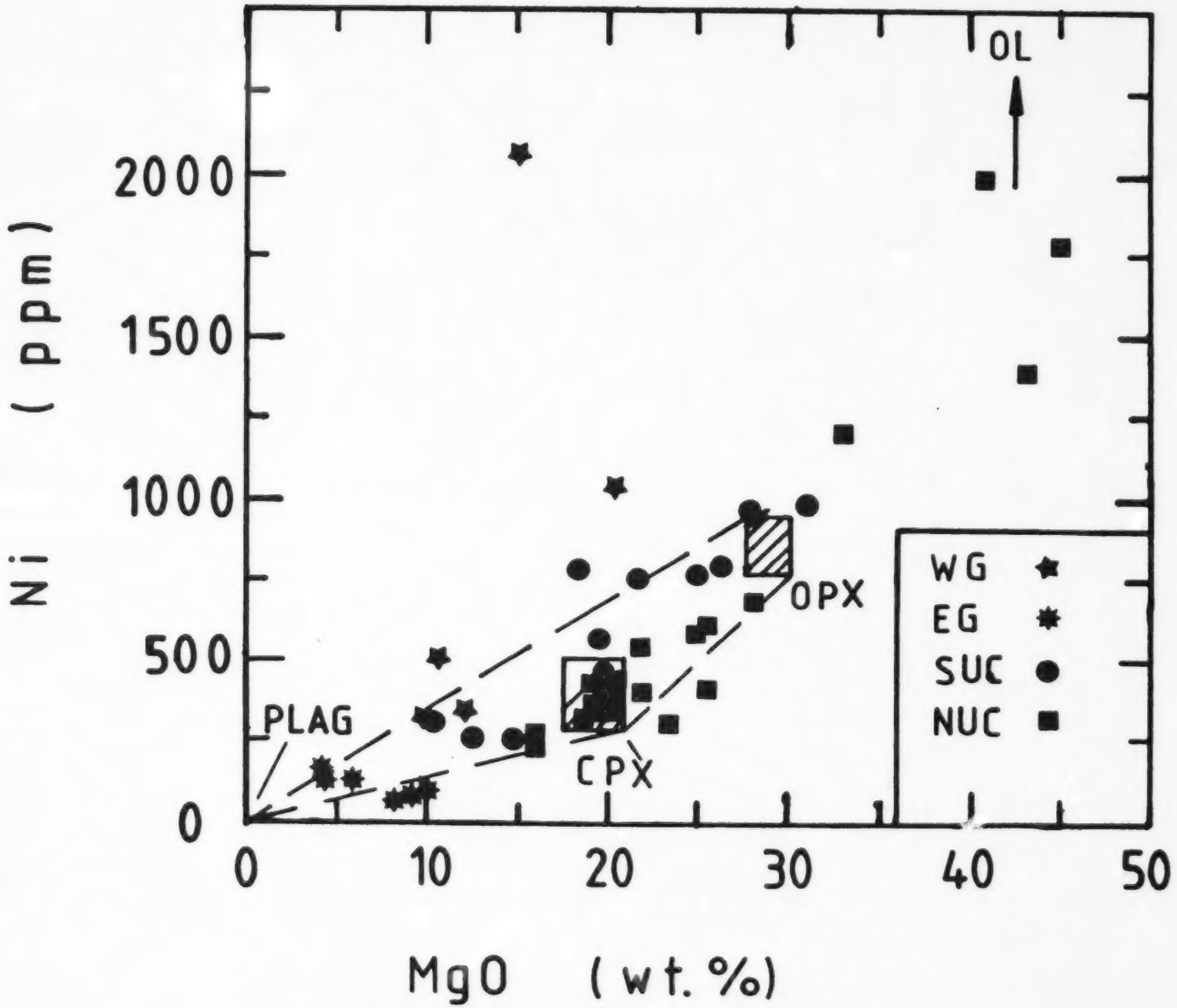
Sulfide poor
Dunite
100
10
1
SAMPLE / PRIM. MANTLE
Co Ni Os Ir Ru Rh Pt Pd Au Cu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500
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Ni (ppm)
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PLAG
CPX
WG
EG
SUC
NUC
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10
20
30
40
50
MgO (wt.%)

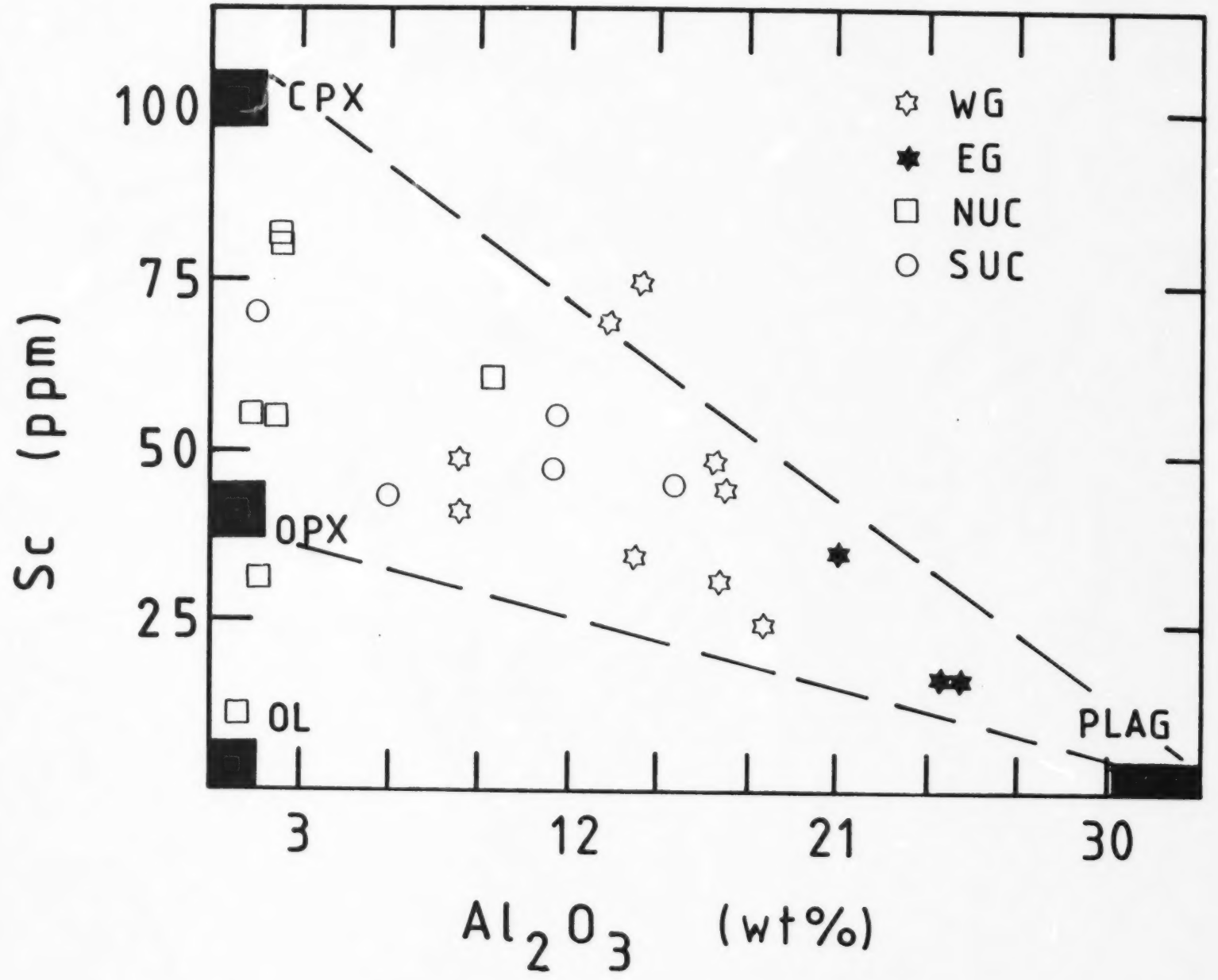


Figure 276.8

Fig 276.8

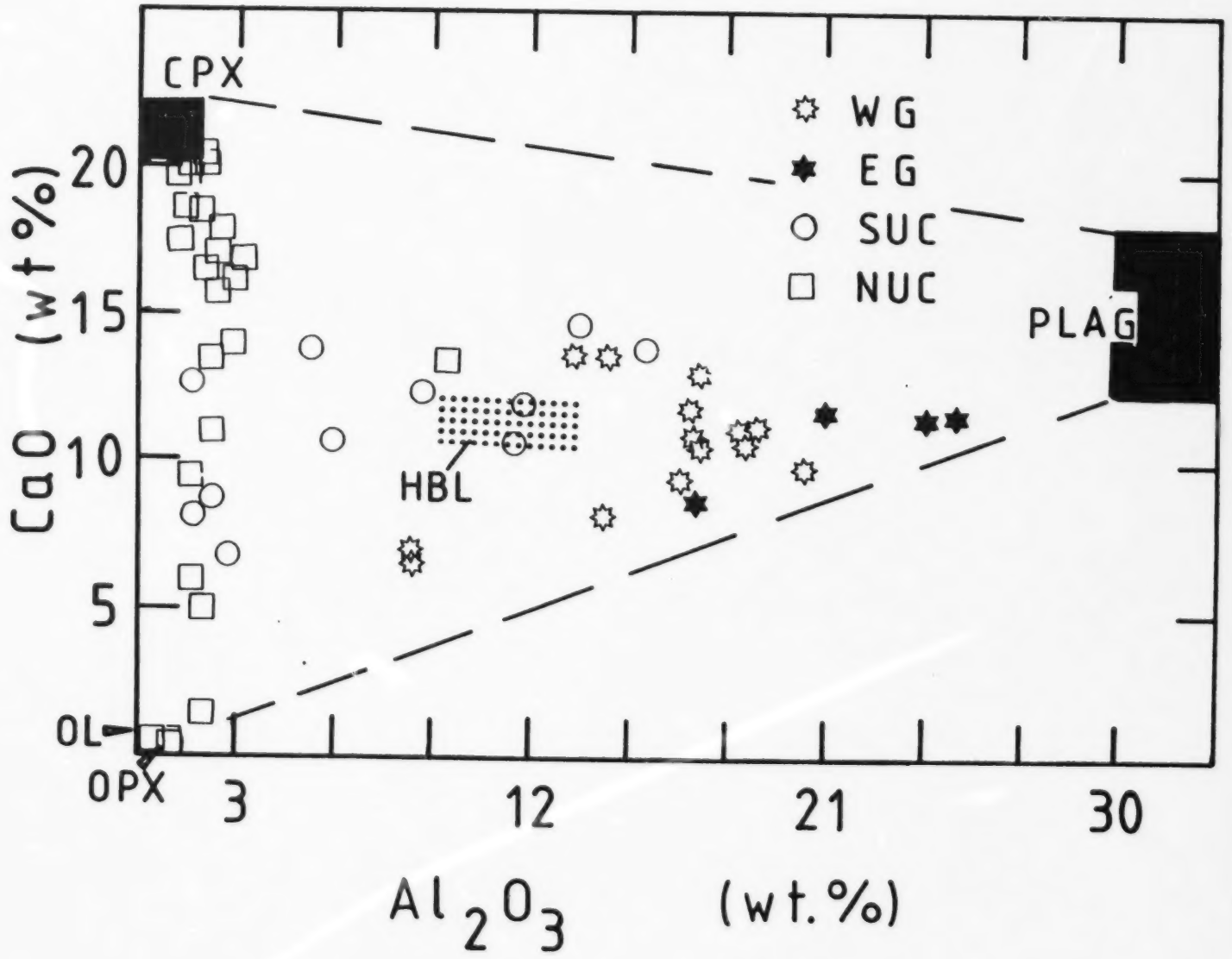


Figure 276.9

276.9

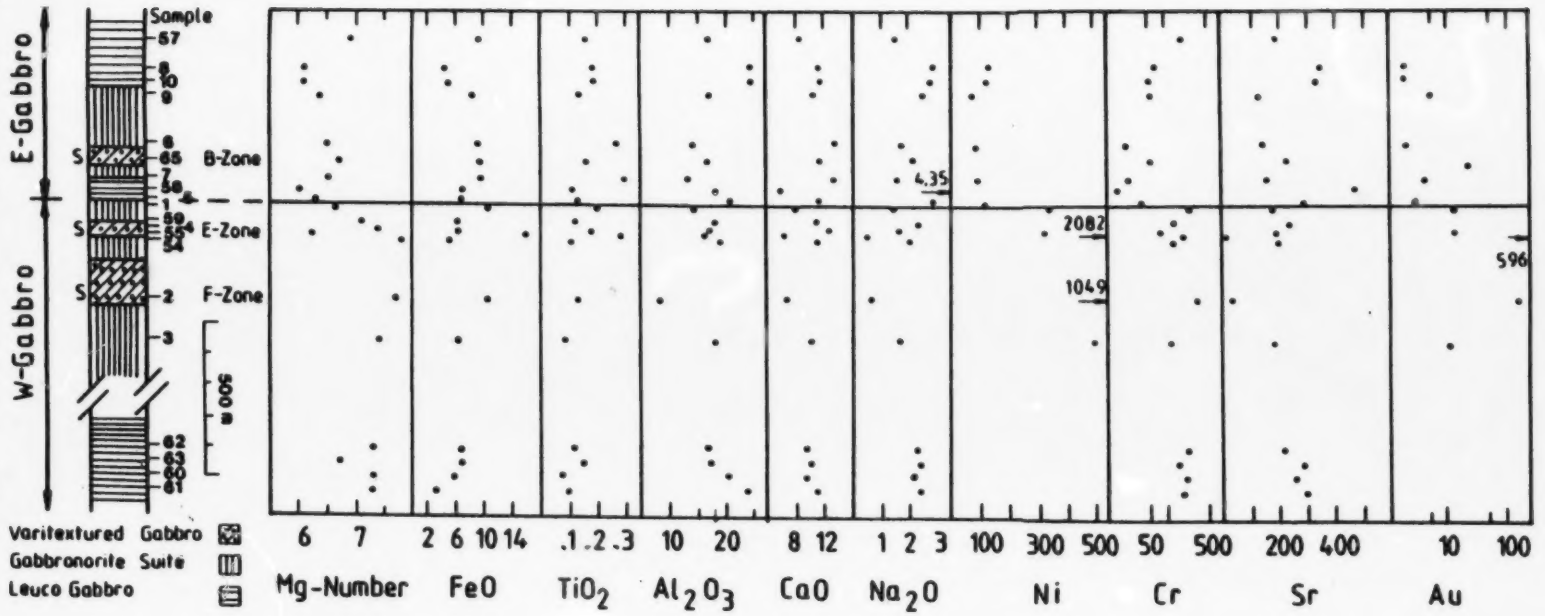


Figure 276.10

276.10

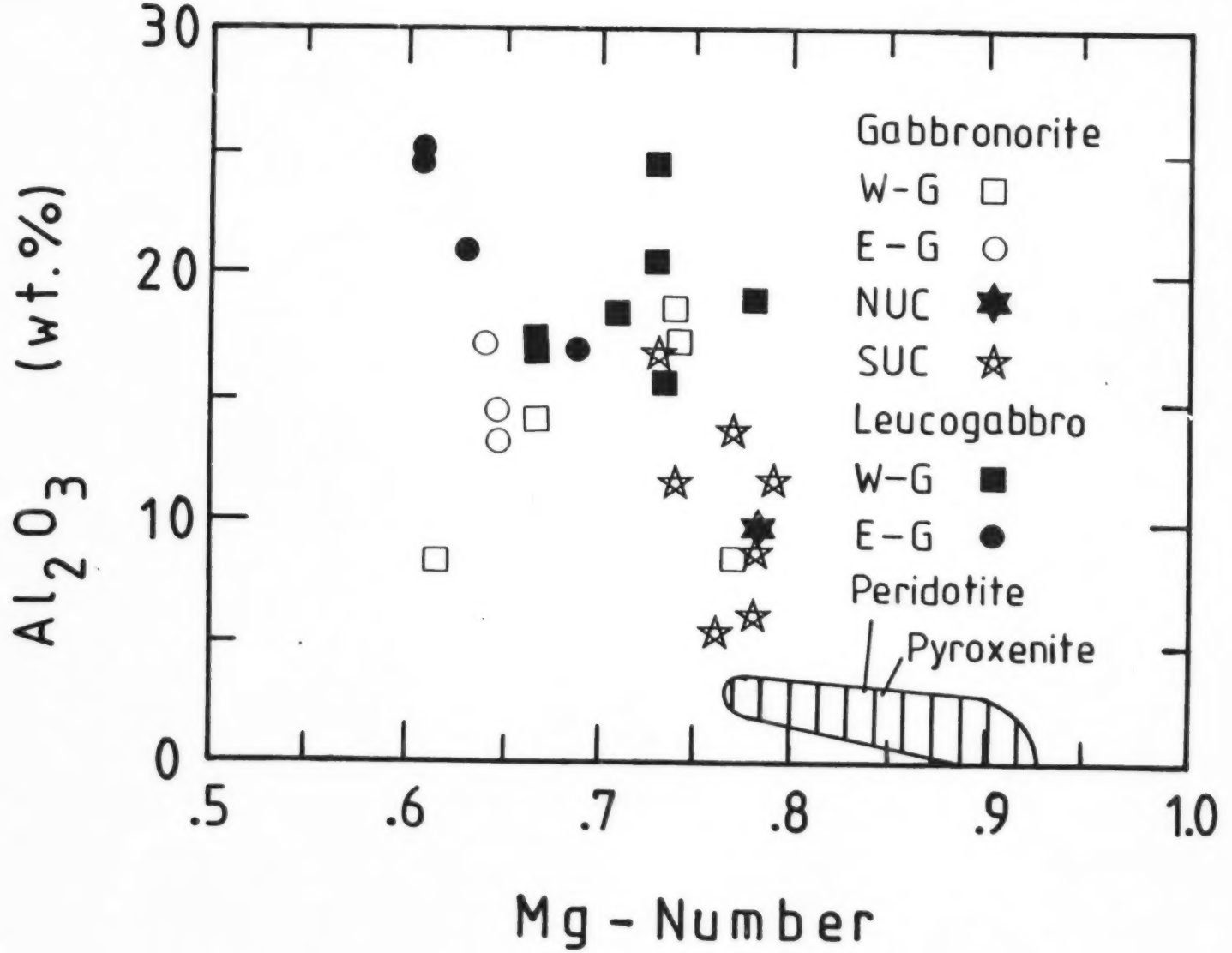


Figure 276.11

276.11

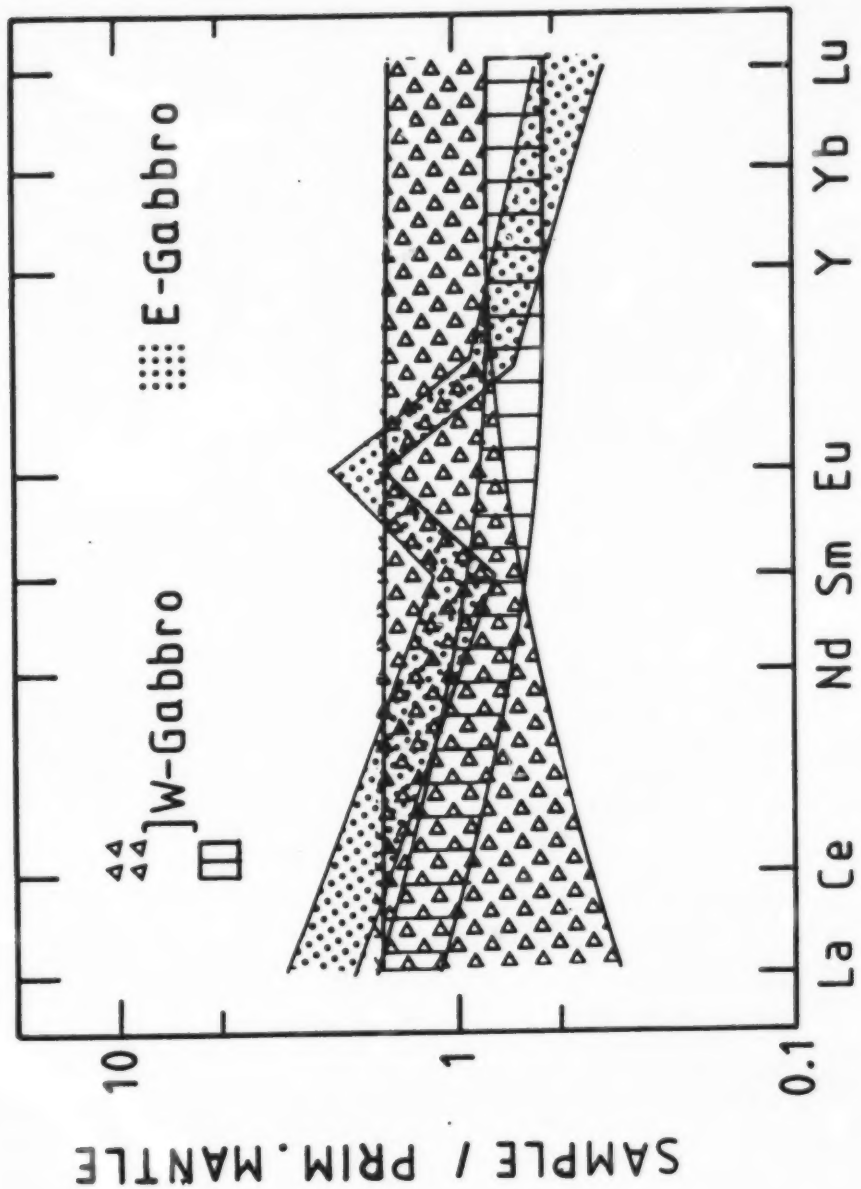
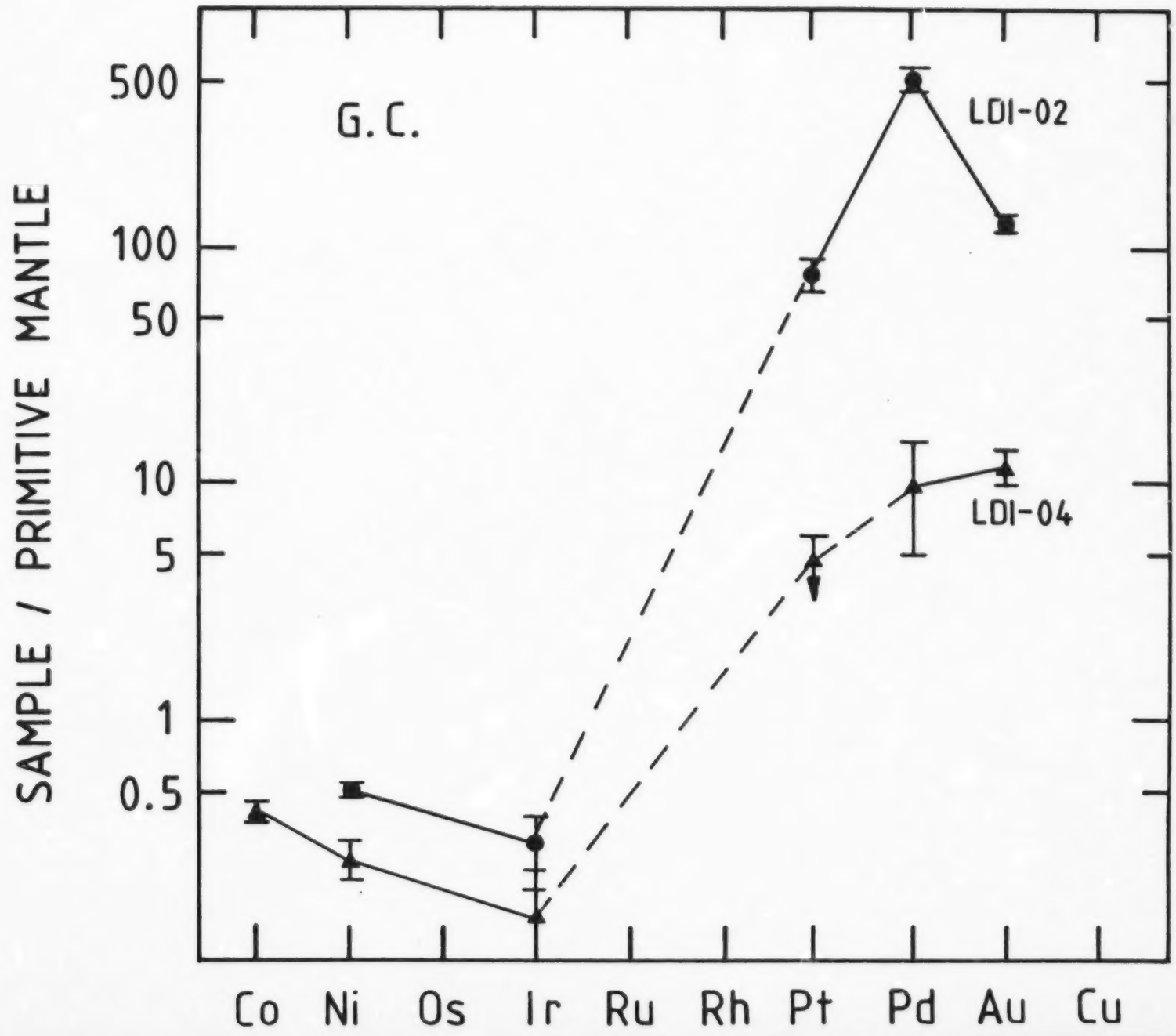


Figure 276. 12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LDI-02
LDI-04
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100
50
10
5
1
0.5
Co
Ni
Os
Ir
Ru
Rh
Pt
Pd
Au
Cu

276.13

3268
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